

Advantages of Muons

- Advantages of leptons over hadrons
 - ◆ Energetic
 - ◆ Interaction simplicity
- Minimal synchrotron radiation at high energies
 - ◆ Can bend: not forced to linac like e^-
 - ★ Reuse accelerating structures
 - ★ Multiple collisions with one beam
 - > Can use larger spot size
 - ◆ No beamstrahlung
 - ★ Won't limit particles per bunch
 - ★ Won't increase effective energy spread
 - ◆ No stochastic radiation equilibrium emittance
- Disadvantages
 - ◆ Finite lifetime
 - ★ Determines many design choices
 - ★ Choices lead to other problems
 - ◆ High energy: neutrino radiation
 - ★ Highly penetrating

General Considerations

- Longitudinal emittance of bunch small
 - ◆ Acceleration in RF (wavelength)
 - ◆ Cost reduction if smaller
 - ◆ Energy acceptance of lattice
- Transverse emittance small
 - ◆ Transport through lattice
 - ◆ Cost reduction if smaller

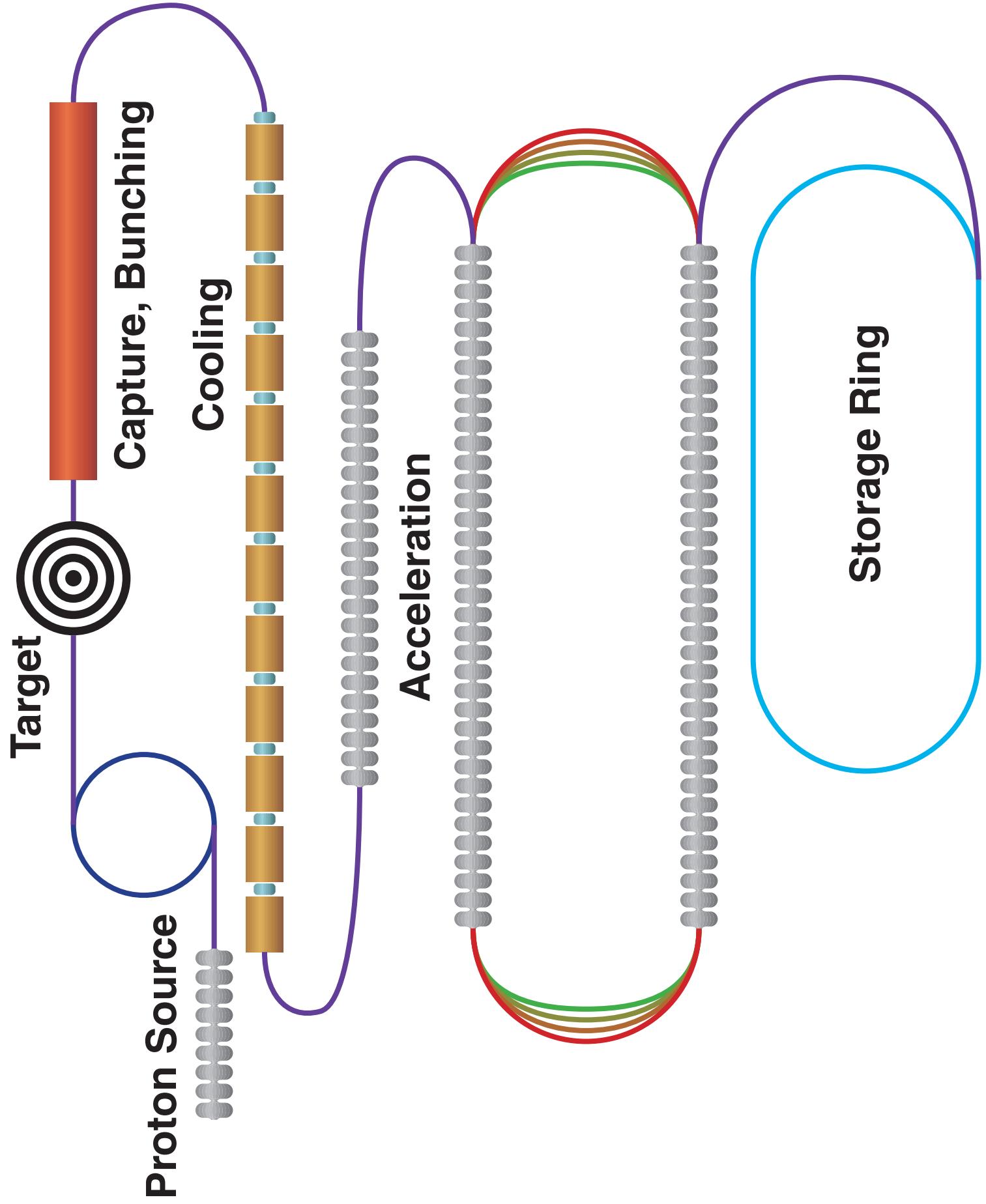
Types of Machines

- Collider

- ◆ Small spot size
- ◆ Large charge per bunch
 - ★ Single bunch of each charge
- ◆ Small longitudinal emittance
 - ★ Short
 - ★ Small energy spread
- ◆ Higgs factory
 - ★ Extremely small energy spread (Higgs width)

- Neutrino factory

- ◆ Only total neutrinos to detector matters
 - ★ Multiple bunch scheme fine
- ◆ Single charge
- ◆ Physics gives modest limitations on beam size
 - ★ Transverse angular spread
- ◆ Studies
 - ★ Fermilab: 50 GeV, low yield
 - ★ BNL: 20 GeV, higher yield (2×10^{20} muons/year)



Muon Production

- Proton hits target, pions decay to muons
- Quantity
 - ◆ Roughly proportional to proton energy
 - ◆ Better for higher Z
 - ★ Difference greater for higher energies
- Proton source
 - ◆ Measure in MW power on target: energy proportionality
 - ◆ 1-4 MW
 - ◆ Radiation at target
 - ◆ Upgrade existing machines (Fermilab, BNL)
- Target survival
 - ◆ Temperature rise
 - ◆ Shock stresses

Muon Production, cont.

- Proposed solutions

- ◆ Carbon

- ★ Fermilab study
 - ★ Lower energy deposition in study, less chance of destruction
 - ★ Lower yield
 - ★ Lower ΔT

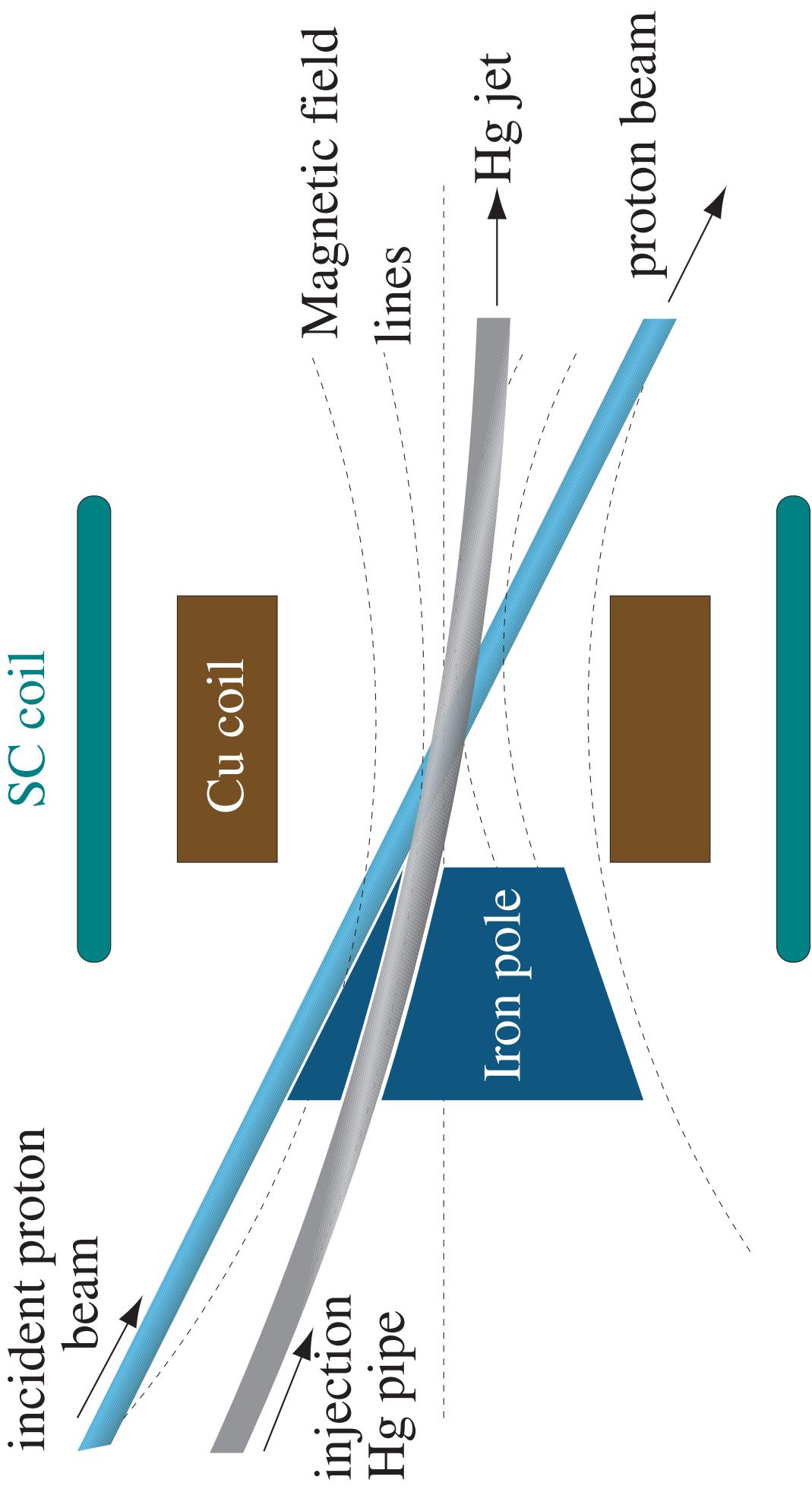
- ◆ Liquid Hg

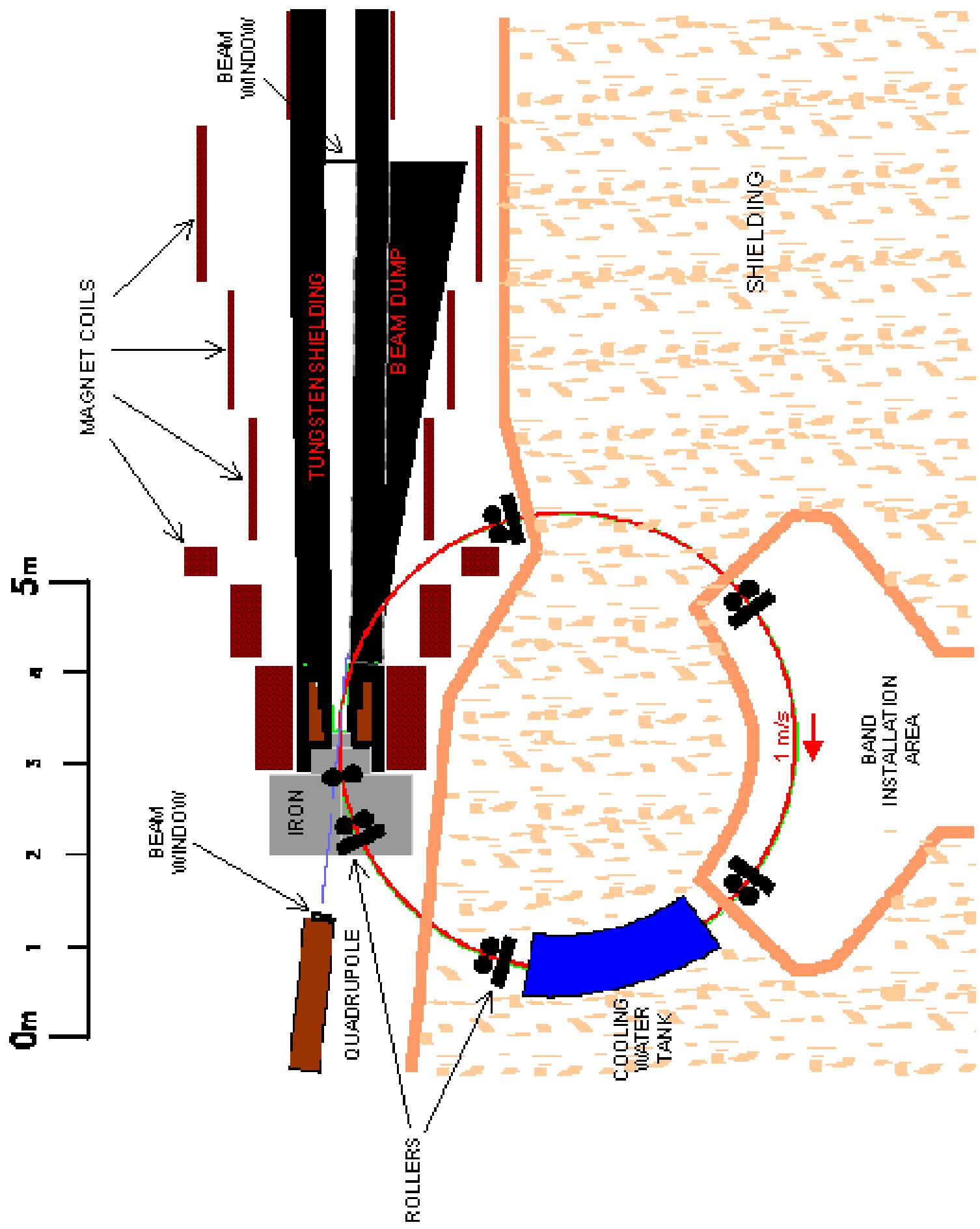
- ★ Avoid target destruction concerns
 - ★ Experiment planned

- ◆ Rotating Cu-Ni band

- ★ Spread beam out

- Radiation, handling





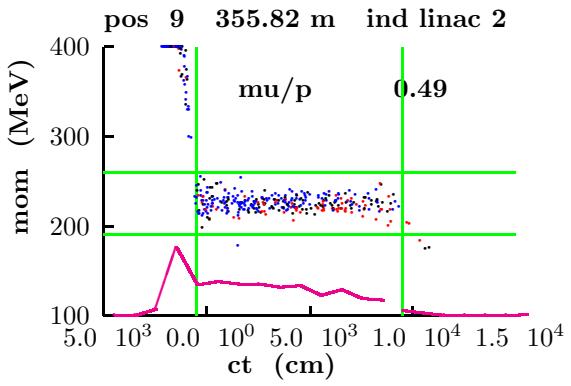
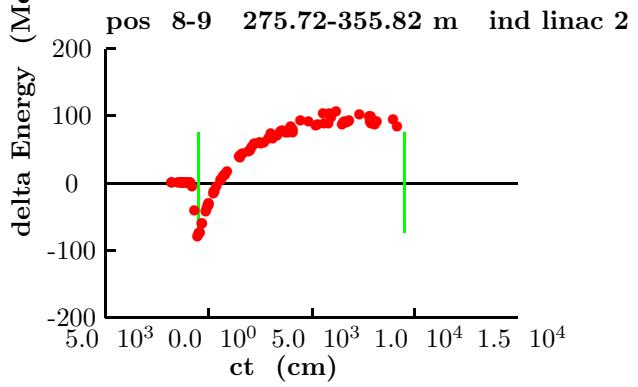
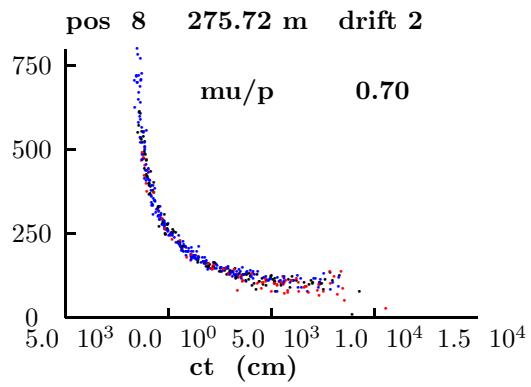
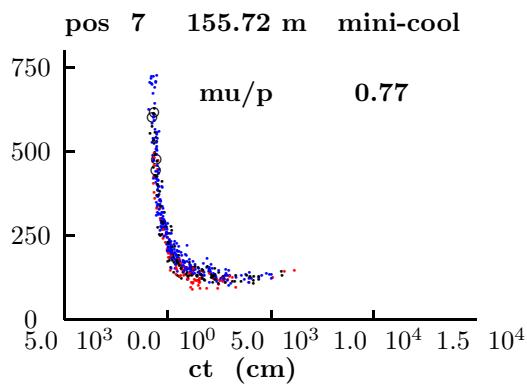
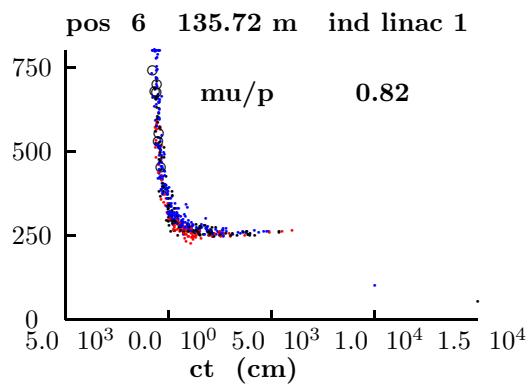
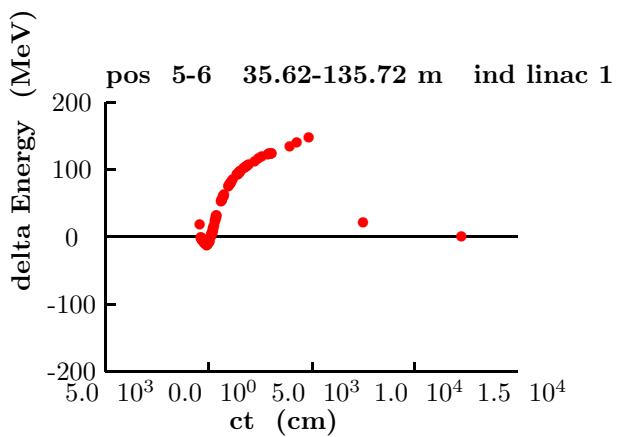
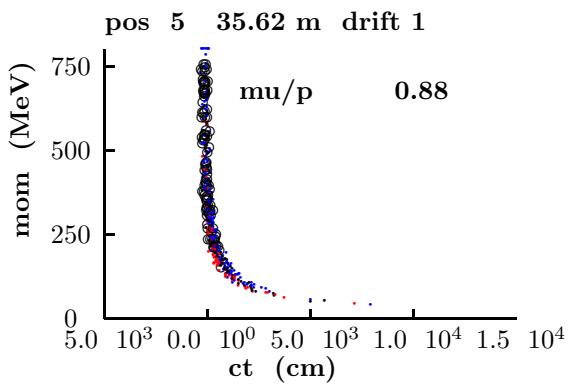
Capture

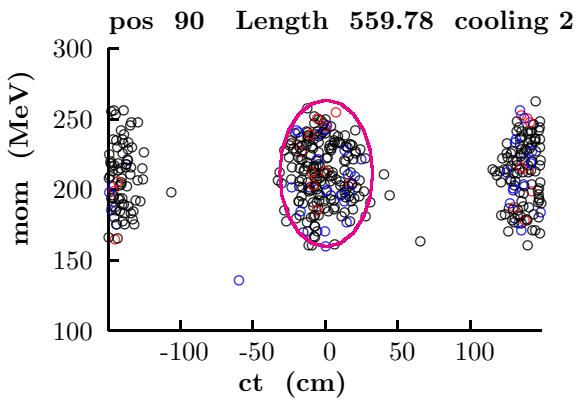
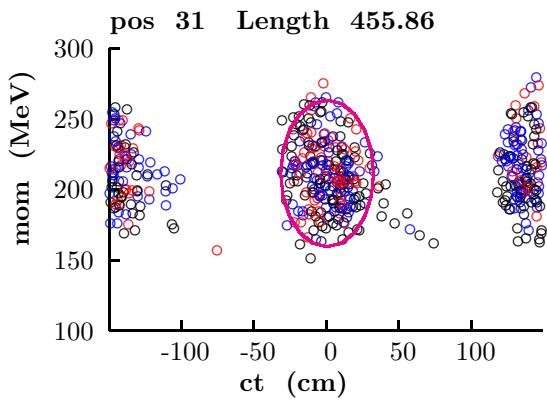
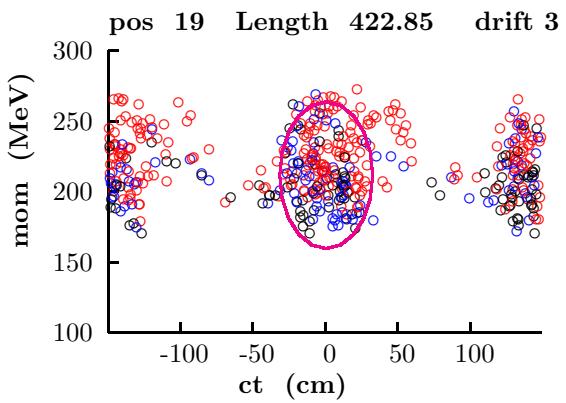
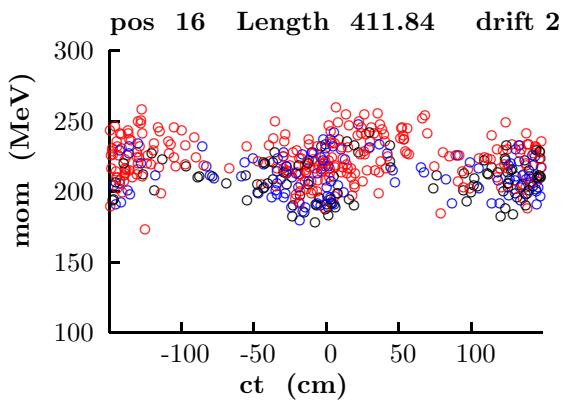
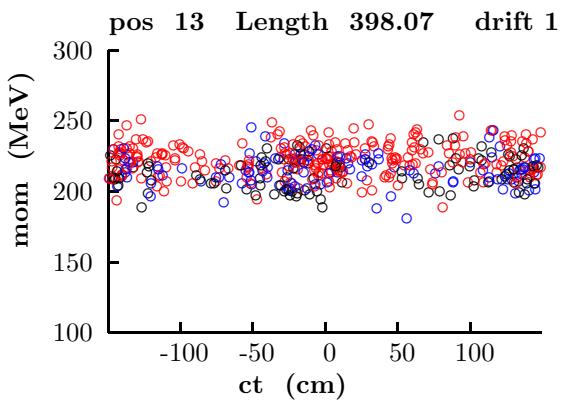
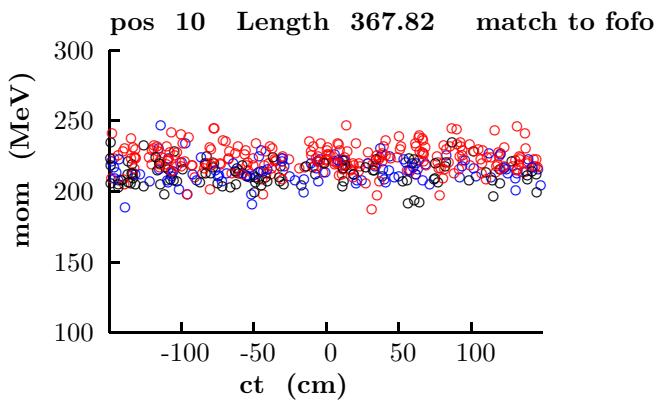
- Neutrino factory

- ◆ Create long bunch with small energy spread
 - ★ Drifts: nonlinear
 - ★ Induction linac (long pulse, RF won't work)
- ◆ Split into smaller bunches
 - ★ Needed small energy spread
 - ★ Lossy
 - > Fast: lose in-between particles
 - > Adiabatic: decay

- Muon collider

- ◆ Want everything in one bunch
- ◆ Have low-frequency RF close to target





Cooling

- Principles

- ◆ Why:

- ★ Event rate proportional to beam density (collider)
- ★ Angular spread small (neutrino factory)
- ★ Losses in transporting large beam
- ★ Cost of transporting larger beam

- ◆ Ionization cooling

- ★ Other methods too slow

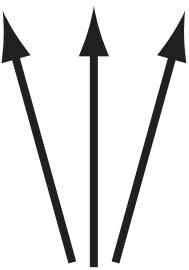
- ◆ Basic cooling

- ★ Lose energy in material
- ★ Momentum reduced in all directions
- ★ Restore longitudinal momentum only with RF
- ★ Result: transverse momentum reduced
- ★ Small effect longitudinally
 - > Derivative of dE/dx with energy
 - > Causes growth in our case

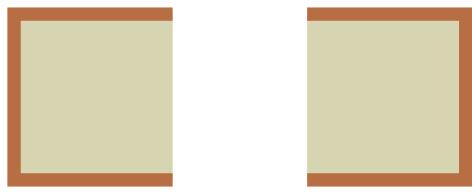
- ◆ Stochastic scattering

- ★ Given angular kicks
- ★ Keep RMS angle large in absorbers
 - > Relative effect small
 - > Difficult at higher energy

Absorber



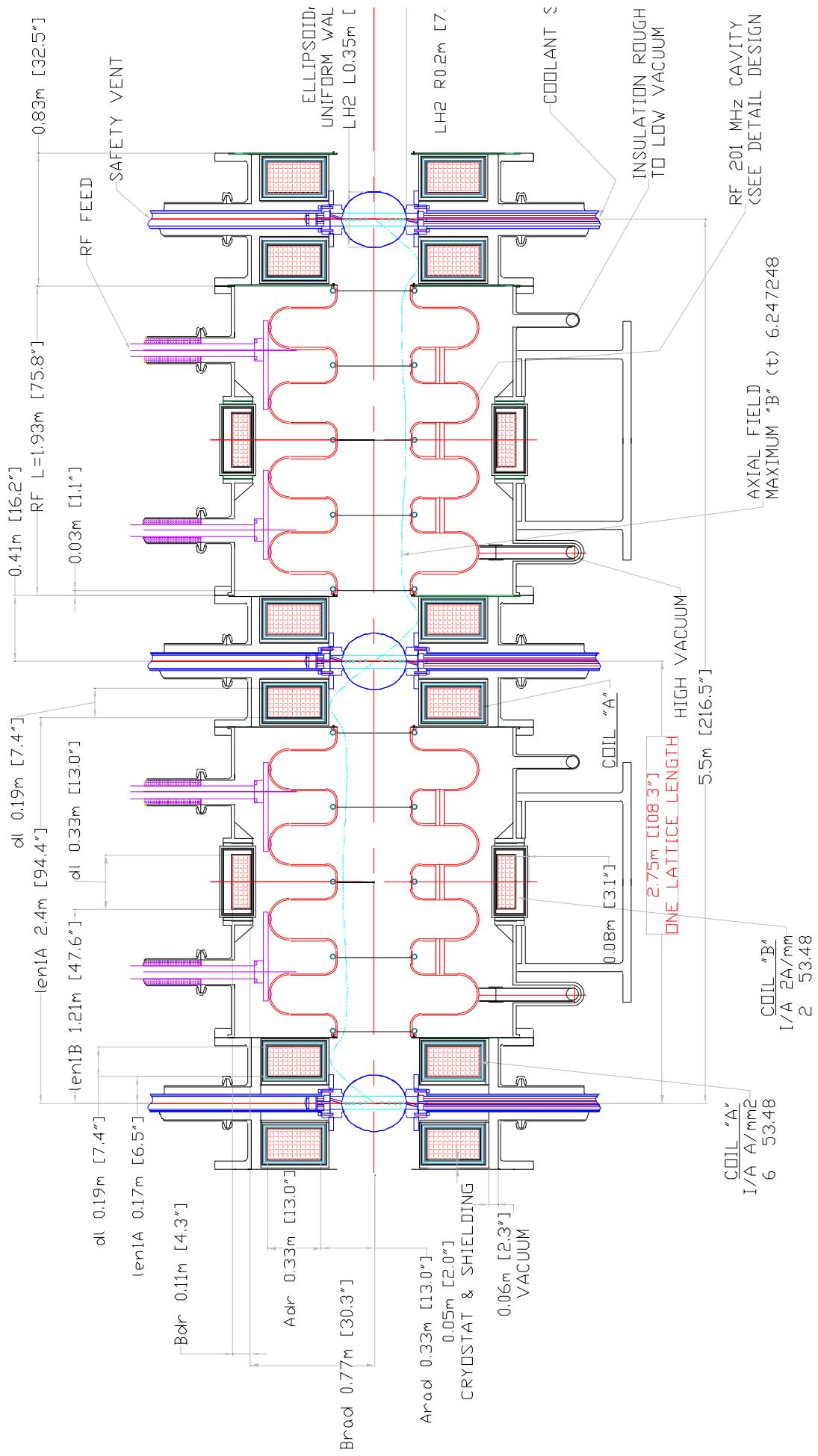
RF Cavity



Cooling, cont.

- Lattice

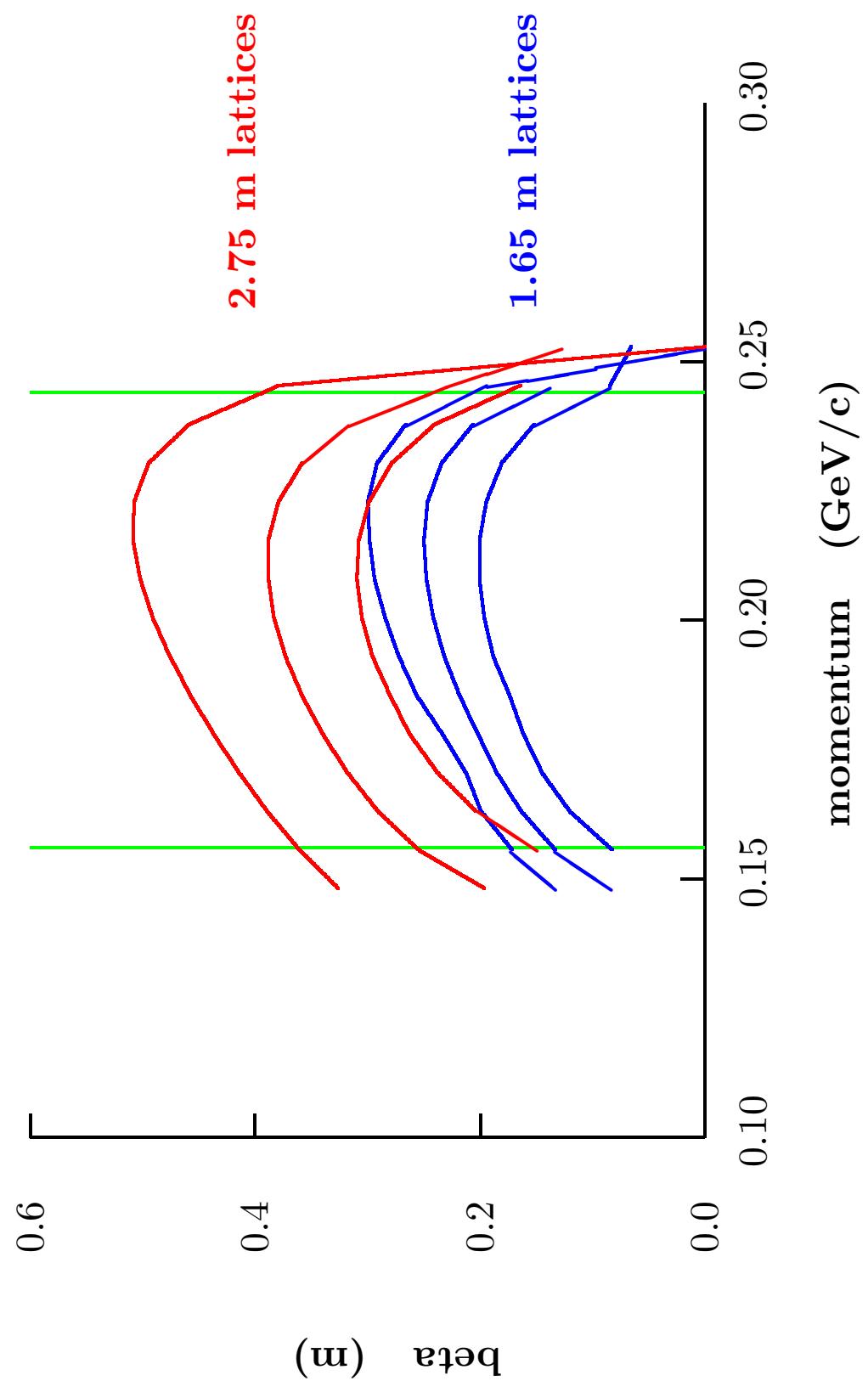
- ◆ Solenoid focusing
 - ★ Large beam
 - ★ Keep angle large
 - ★ High fields
 - ★ Requires NC RF: large power requirement
- ◆ Large energy spread
 - ★ Running between resonances
 - ★ Matching, linear modeling difficult
- ◆ Full longitudinal bucket
 - ★ Particles slowly spilling out longitudinally
- ◆ Figure of merit
 - ★ Particles within acceptance of downstream systems
 - ★ Increasing acceptance of downstream:
significant cost increase
- ◆ Emittance profile

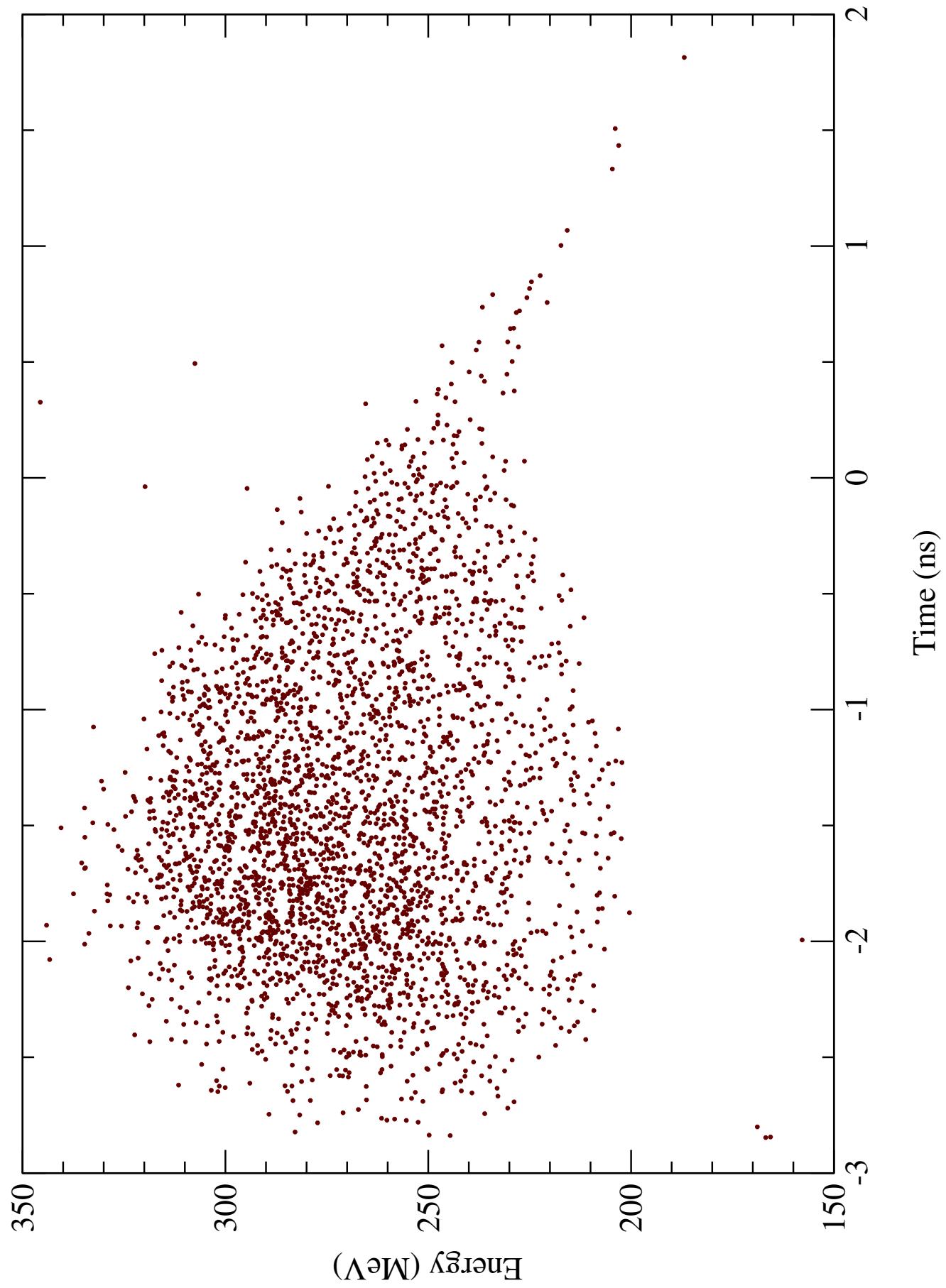


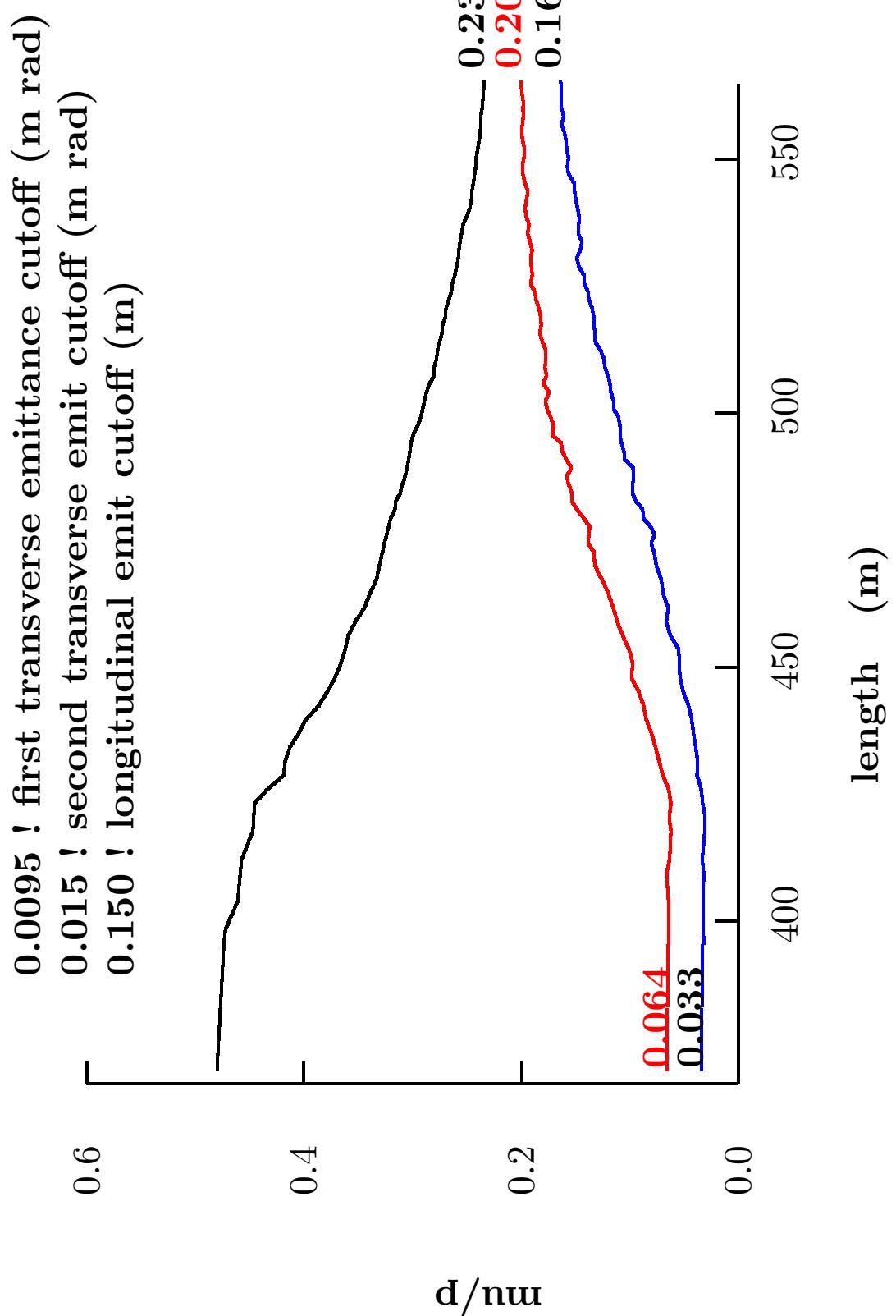
Super FOF LATTICE
at start of cooling
(PRELIMINARY)

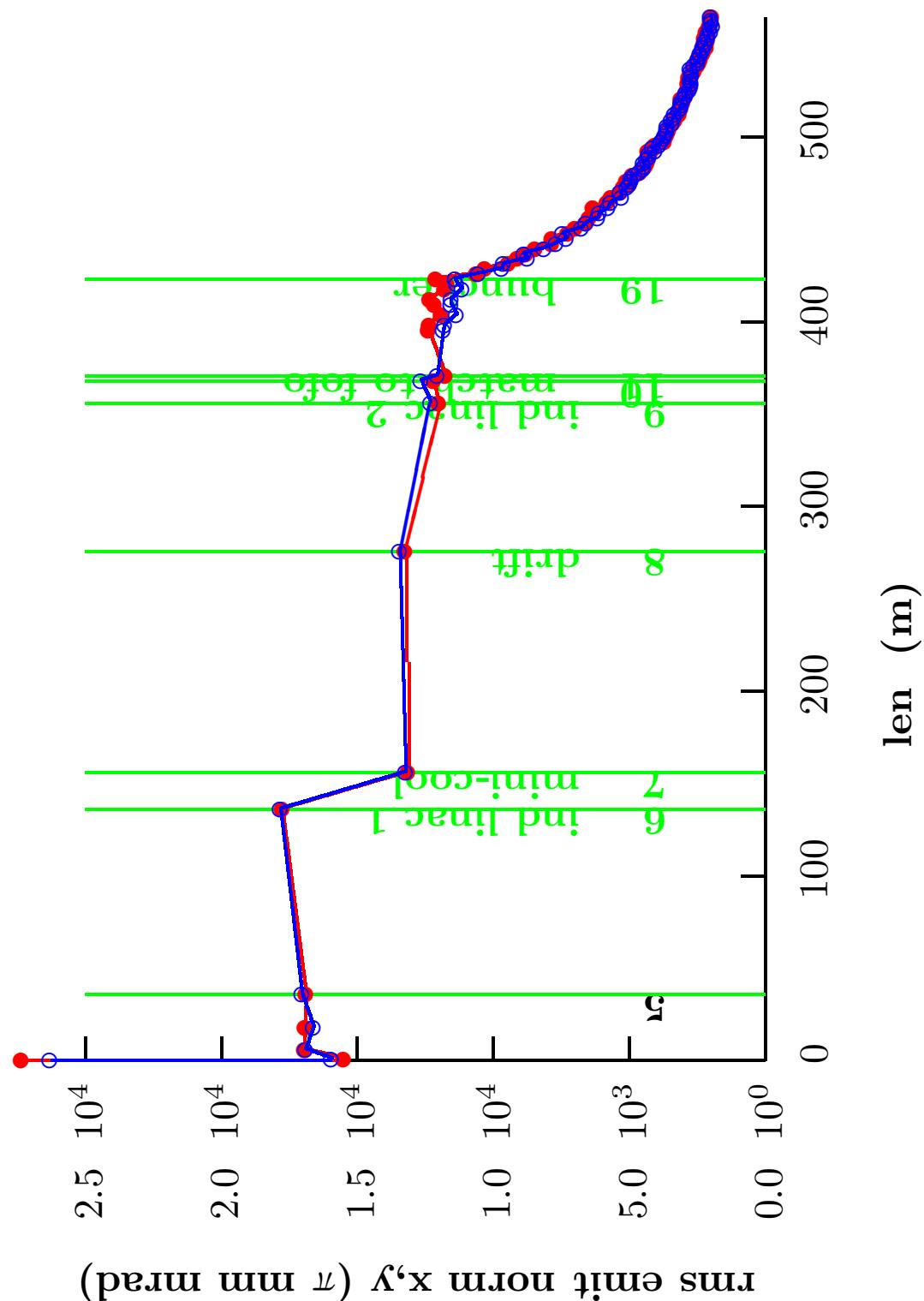
SFOF START 201MHz rev1

E.L.BLOCK IIT
6/22/2000
6/28/2000 REV.









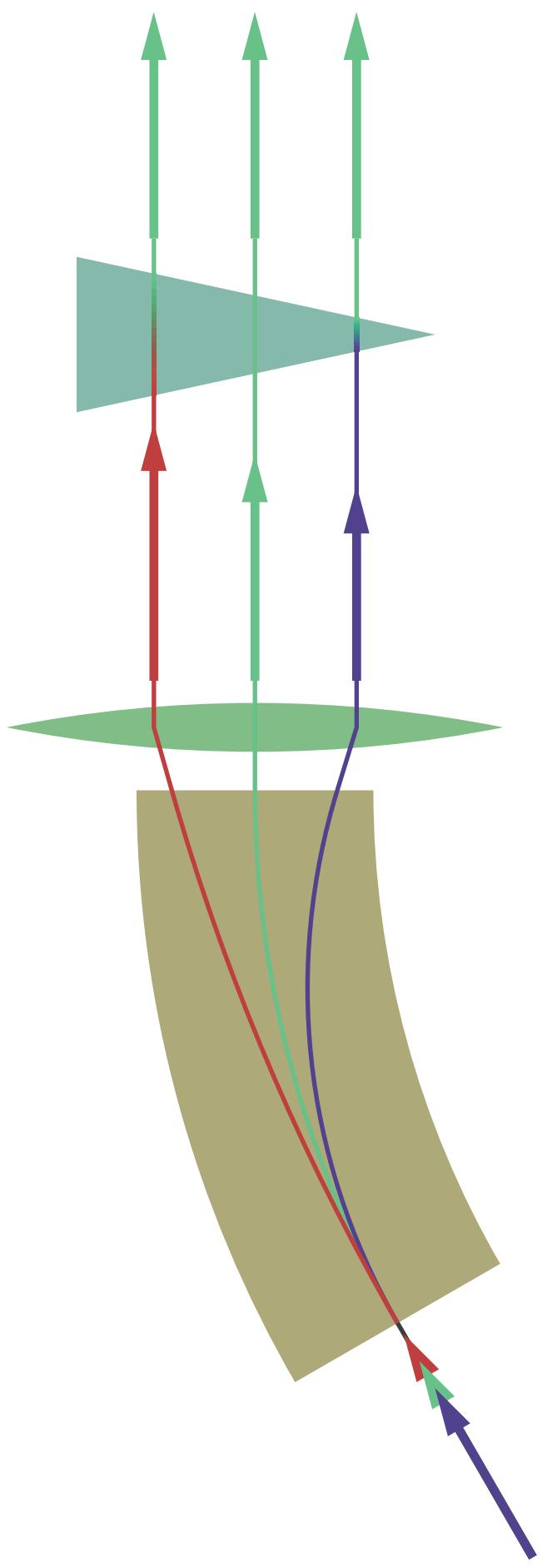
Emittance Exchange

- Longitudinal Cooling

- ◆ Needed for collider (hourglass)
- ◆ Reduces cost of acceleration
- ◆ More cooling: not falling out of bucket

- Principle

- ◆ Create position dependence on energy (dispersion)
- ◆ Wedge of absorber:
 - ★ Energy loss depends on position
 - ★ Dispersion: energy loss depends on energy
 - ★ Reduce energy spread
- ◆ Cost: increased beam size
- ◆ Result: traded longitudinal beam size (emittance) for transverse
- ◆ Other methods
 - ★ Can completely exchange longitudinal phase space plane with one transverse
 - ★ Create rotated phase space at absorber: all three phase space planes have transverse momentum component



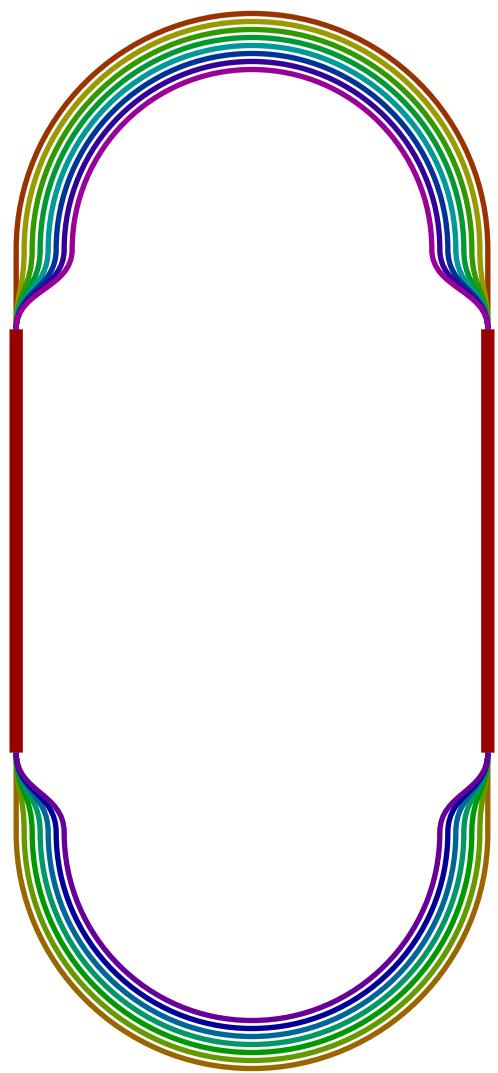
Emittance Exchange, cont.

- Practical

- ◆ Have shown short sections with damping in all three phase space planes
- ◆ Longer sections more difficult
 - ★ Large beam size: linear approximation not so hot
 - ★ Difficult to match in 6-D phase space
 - ★ Bent solenoids

Acceleration

- Major cost driver
- Must begin with linac
 - ◆ Large energy spread: difficult to bend
- Recirculating accelerator (CEBAF-style)
 - ◆ Principles
 - ★ Can bend muons, so reuse linac
 - ★ Need lots of RF per turn: decay
 - ◆ Large energy spread in arcs (around $\pm 10\%$)
 - ★ Emittance blowup
 - ◆ Keep peak power low
 - ★ SCRF
 - ★ Long fill times

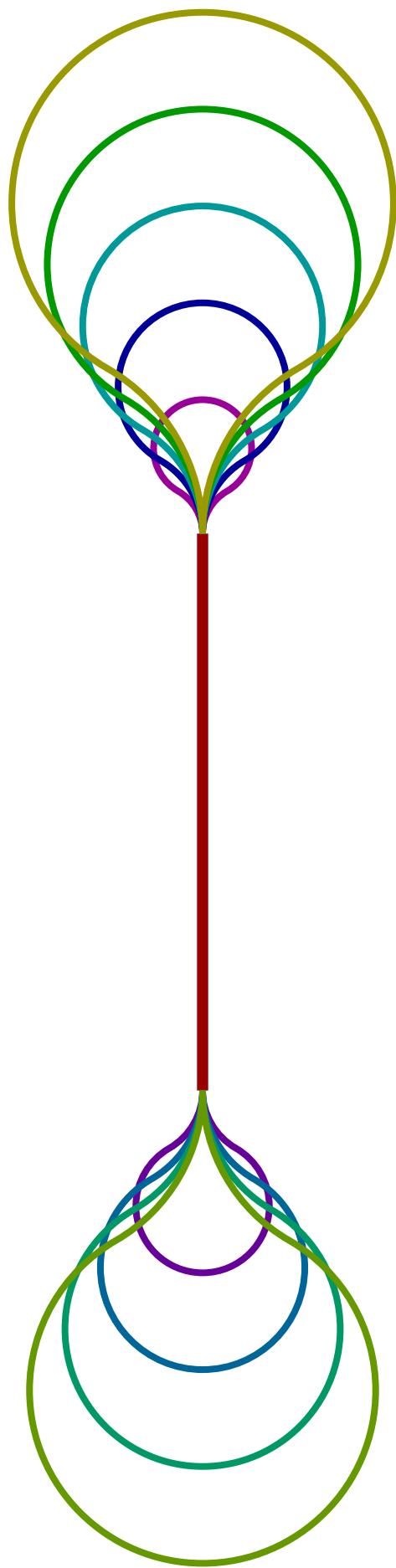


Acceleration, cont.

- ◆ Large current: beam loading
 - ★ No time to replace extracted power
 - ★ Energy extracted by beam
 - > Just a couple percent: allows several passes
 - ★ Neutrino factory: bunch trains
 - > Front bunch extracts energy
 - > Rear bunch sees less voltage
 - > Different bunches have different energies after acceleration
 - ★ Collider: potential well distortion
 - ★ Need synchrotron oscillations
 - > Bunch loses too much energy
 - > Falls back, gains more energy
 - > Result: oscillations about correct energy
 - > More synchrotron oscillation, smaller amplitude oscillations
 - ★ Another option: use two close RF frequencies, beat wave
 - > On slope of beat wave, slope matches beam loading RF loss
 - > Waste linac: difference between gradient used and peak gradient

Acceleration, cont.

- ◆ Geometry choices
 - ★ Racetrack: traditional design
 - ★ Dogbone
 - > Use same linac in both directions: cost savings
 - > Arcs get slightly longer
 - > Cost optimization
 - > Less complex switchyard
 - > Reverse bends
 - > Crossing lines
 - ★ Multi-sided
 - > Handle instabilities: create more synchrotron oscillations
 - > Overhead associated with switchyards greater
- ◆ FFAG arcs
 - ★ Re-use arcs, but arcs more expensive
 - ★ Avoid switchyards
 - ★ Energies can overlap:
 - > More turns
 - > More efficient RF use
 - > More decays
 - ★ Timing bunch to RF
 - > Isochronous arcs: no synchrotron oscillations, beam loading, sufficiently isochronous
 - > Shift RF phase: difficult

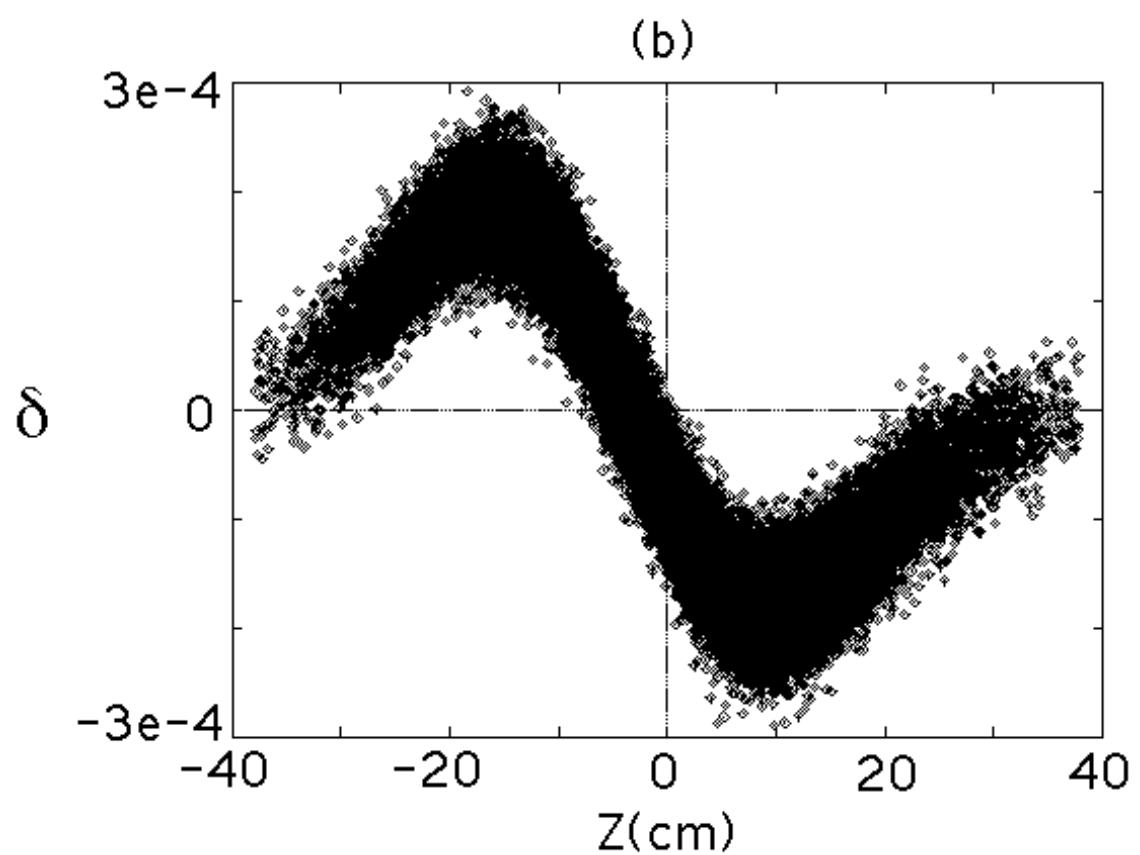
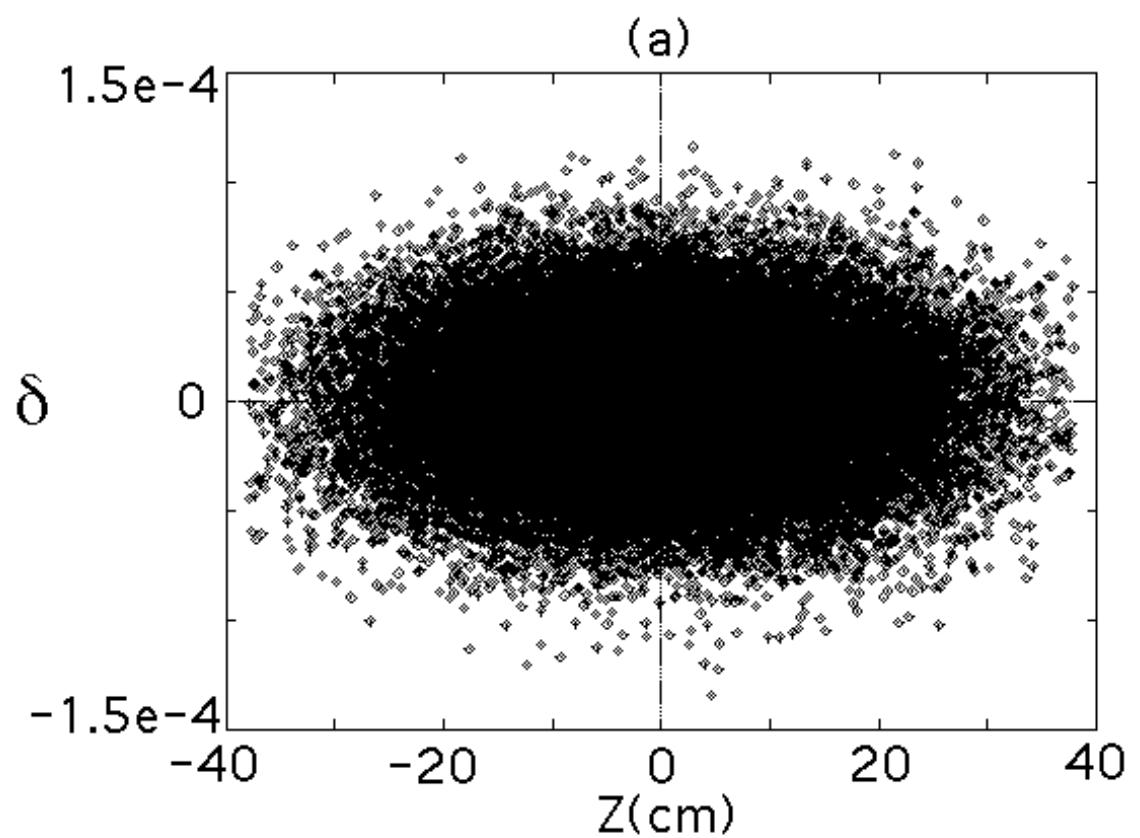


Storage Ring

- Neutrino factory
- Long straights, pointed toward neutrino detector
 - ◆ Sloped
 - ◆ Deep underground: groundwater (limits BNL energy)
 - ◆ Longer straights, better efficiency
 - ★ Diminishing returns
 - ◆ Triangular, bowtie shape for two detectors
- Large energy spread (2%, better than the rest of system)
- Few hundred turns

Collider: Higgs Factory

- Low energy (50+50)
- 1000 turns or so
- Extremely small energy spread (3×10^{-5})
- Collective effects
 - ◆ Large single bunch current
 - ◆ Infinite-time unstable
 - ★ Only 1000 turns: OK over that time frame
 - ◆ Wakefields increase energy spread
 - ★ RF cavities to correct
- Design being studied (Cline & Hanson)



Collider: High Energy

- Neutrino radiation at high energies
- Being studied (Caldwell & King)

TABLE 1. Straw-man muon collider parameters. See overview write-up for details.

center of mass energy, E _{CoM} description	0.1 to 3 TeV MCC status report	400 GeV top threshold	4 TeV frontier	30 TeV many-TeV
collider physics parameters:				
luminosity, \mathcal{L} [cm ⁻² .s ⁻¹] $\int \mathcal{L} dt$ [fb ⁻¹ /year]	(0.08 → 700) × 10 ³² 0.08→700 650→13 000	3.0 × 10 ³³ 30 16 000	5.0 × 10 ³³ 50 270	3.0 × 10 ³⁵ 3000 290
No. of $\mu\mu \rightarrow ee$ events/det/year	2000→800 000	14 000	55 000	5 × 10 ⁶
No. of (115 GeV) SM Higgs/year	0.02→1.1	1.4	1.0	0.14
CoM energy spread, σ_E/E [10 ⁻³]				
collider ring parameters:				
circumference, C [km]	0.35→6.0	1.0	8.7	45
ave. bending B field [T]	3.0→5.2	4.2	4.8	7.0
beam parameters:				
(μ^- or) μ^+ /bunch, N_0 [10 ¹²]	2.0→4.0	4.0	3.5	2.3
(μ^- or) μ^+ bunch rep. rate, f_b [Hz]	15→30	15	1.0	7.5
6-dim. norm. emit., ϵ_{6N} [10 ⁻¹² m ³] ϵ_{6N} [10 ⁻⁴ m ³ .MeV/c ³]	170→170 2.0→2.0	170	170	100
P.S. density, N_0/ϵ_{6N} [10 ²² m ⁻³]	1.2→2.4	2.4	2.2	2.3
x,y emit. (unnorm.) [$\pi.\mu\text{m.mrad}$]	3.5→620	41	2.4	0.19
x,y normalized emit. [$\pi.\text{mm.mrad}$]	50→290	77	46	27
long. emittance [10 ⁻³ eV.s]	0.81→24	10	28	48
fract. mom. spread, δ [10 ⁻³]	0.030→1.6	2.0	1.4	0.20
relativistic γ factor, E_μ/m_μ	473→14 200	1890	18 900	142 000
time to beam dump, t_D [$\gamma\tau_\mu$]	no dump	no dump	0.5	no dump
effective turns/bunch	450→780	620	450	1040
ave. current [mA]	17→30	24	0.63	12
beam power [MW]	1.0→29	3.8	2.2	83
synch. rad. critical E [MeV]	5 × 10 ⁻⁷ → 8 × 10 ⁻⁴	1.1 × 10 ⁻⁵	0.0013	0.11
synch. rad. E loss/turn	7 eV → 0.3 MeV	0.6 keV	700 keV	450 MeV
synch. rad. power	0.1 W → 10 kW	15 W	470 W	5.2 MW
beam + synch. power [MW]	1.0→29	3.8	2.2	88
decay power into beam pipe [kW/m]	1.0→2.1	2.1	0.06	0.8
interaction point parameters:				
rms spot size, $\sigma_{x,y}$ [\mu m]	3.3→290	18	2.7	1.0
rms bunch length, σ_z [mm]	3.0→140	7.5	3.0	4.8
$\beta_{x,y}^*$ [mm]	3.0→140	7.5	3.0	4.8
rms ang. divergence, σ_θ [mrad]	1.1→2.1	2.3	0.90	0.20
beam-beam tune disruption, $\Delta\nu$	0.015→0.051	0.056	0.083	0.092
pinch enhancement factor, H_B	1.00→1.01	1.02	1.08	1.09
beamstrahlung frac. E loss/collision	negligible	negligible	6 × 10 ⁻⁹	9 × 10 ⁻⁸
final focus lattice parameters:				
max. poletip field of quads., $B_{5\sigma}$ [T]	6→12	10	12	15
max. full aper. of quad., $A_{\pm 5\sigma}$ [cm]	14→24	18	18	18
quad. gradient, $2B_{5\sigma}/A_{\pm 5\sigma}$ [T/m]	50→90	110	130	160
approx. β_{\max} [km]	1.5→150	8	140	1800
ff demag., $M \equiv \sqrt{\beta_{\max}/\beta^*}$	220→7100	100	7000	19 000
chrom. quality factor, $Q \equiv M \cdot \delta$	0.007→11	0.003	10	4
neutrino radiation parameters:				
collider reference depth, D[m]	10→300	20	300	100
ave. rad. dose in plane [mSv/yr]	2 × 10 ⁻⁵ →0.02	7 × 10 ⁻⁴	9 × 10 ⁻⁴	6
str. sec. len. for 10x ave. rad. [m]	1.3→2.2	1.6	1.1	1.9
ν beam distance to surface [km]	11→62	16	62	36
ν beam radius at surface [m]	4.4→24	8.4	3.3	0.25